UMassAmherst

Lightweight, High-Temperature Radiator for Space Propulsion

Robert W. Hyers and Briana N. Tomboulian
University of Massachusetts, Amherst, MA

Paul Craven and Jan Rogers
NASA MSFC

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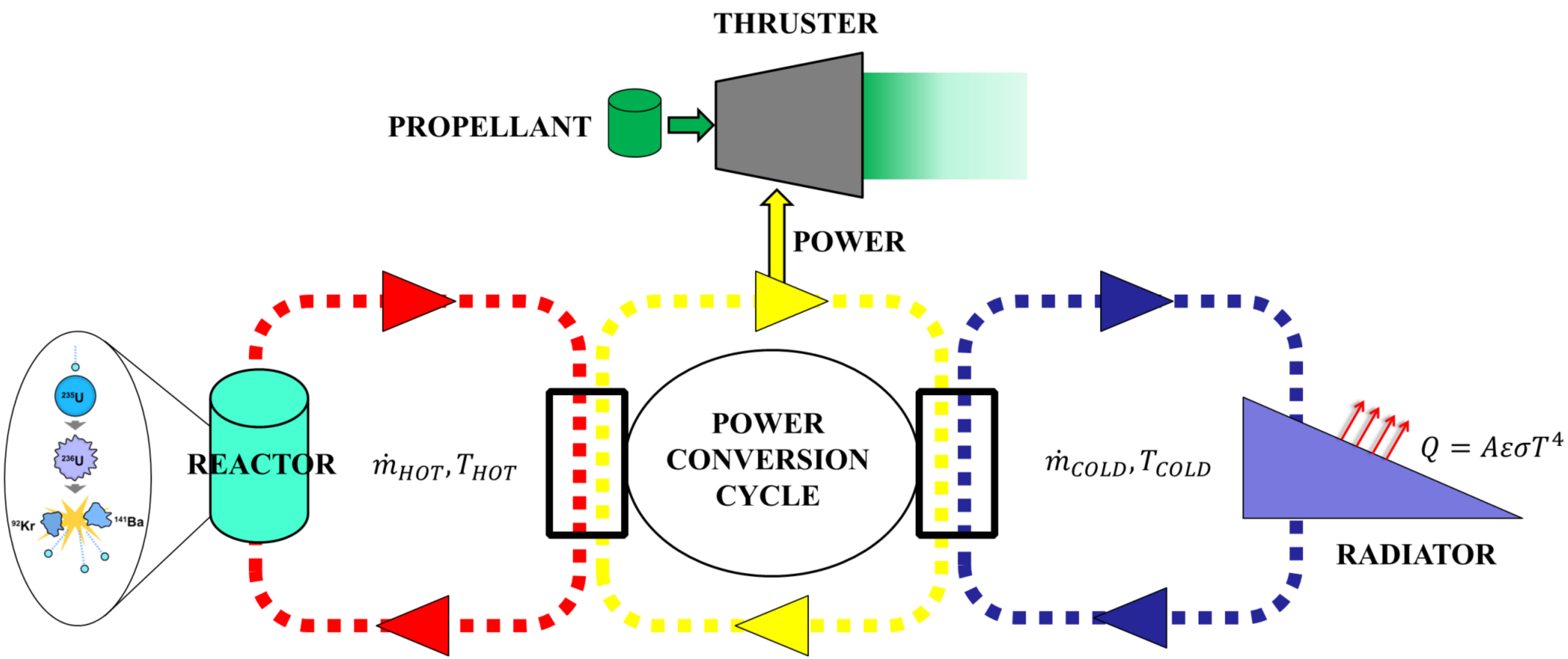
Outline

- Radiators for advanced propulsion
- Materials for radiators
- Modeling and testing novel radiator materials
- Results to date
- Conclusions and Future Work

Nuclear Electric Propulsion (NEP)



NASA's Target Power Level: 100kWe

Heat Rejection

- Radiation is the only heat rejection mechanism to space (no conduction/convection)
- Waste heat depends on
  - Power level
  - Thermal efficiency of the engine

$$\eta_{Th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{waste}}{Q_{in}}$$

- Amount of heat rejection per unit area of radiator
  - Cold-side temperature, T
  - Environmental temperature, T_{env}
  - Surface emissivity, ε

$$q = \varepsilon\sigma\left(T^4 - T_{env}^4\right) \quad \left[\frac{W}{m^2}\right]$$

$$\downarrow$$

$$Area = \frac{Q_{waste}}{\varepsilon\sigma T^4}$$

Why are better radiators required?

- To Date:
  - Previous propulsion methods did not require large radiators:
    - Chemical rockets reject most heat with the exhaust gas
    - Electric propulsion systems have used solar power, which does not require much heat rejection
  - Low temperature heat rejection <100°C
  - Existing radiator designs don't meet NASA's areal density goal for NEP of 2-4 kg/m^2
- Goals:
  - Decrease areal density
  - Increase capabilities
    - High temperature applications
    - Damage tolerance → extended lifespan

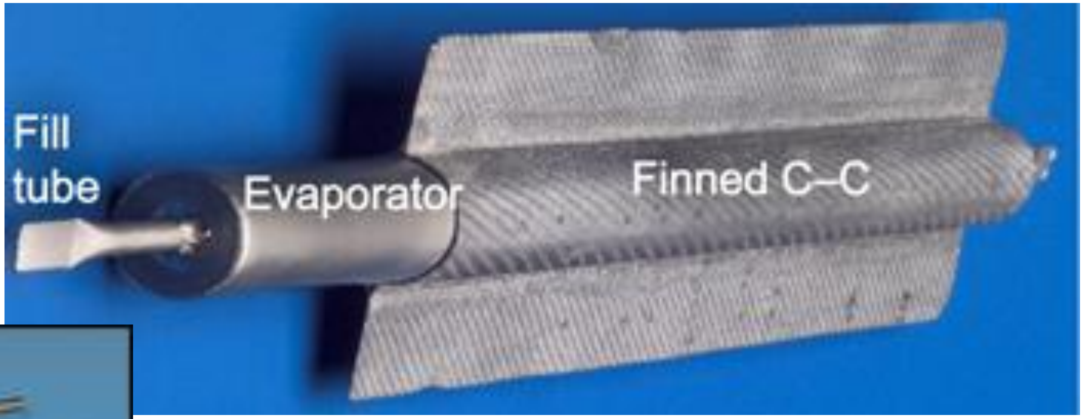
Radiator Mass Reductions

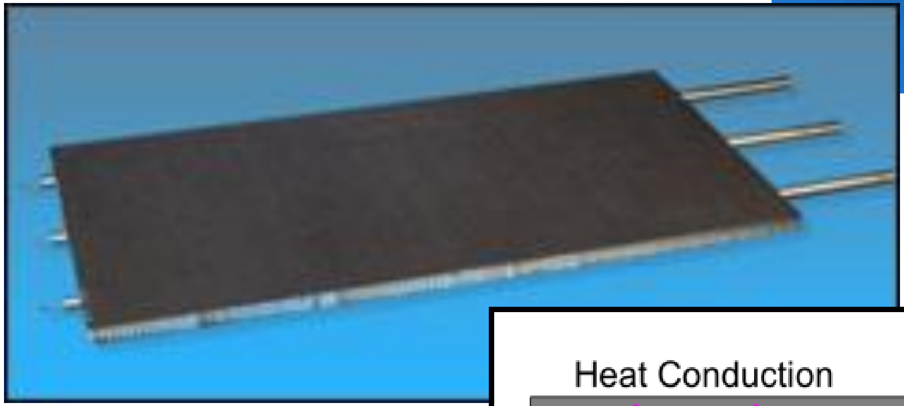
1. Decrease fin areal density
2. Increase fin emissivity (but already→1)
3. Increase cold-side temperature (decreases the fin area)
4. Reduce thermal resistances at interfaces

Even a small increase in efficiency can have a significant impact for a component this large

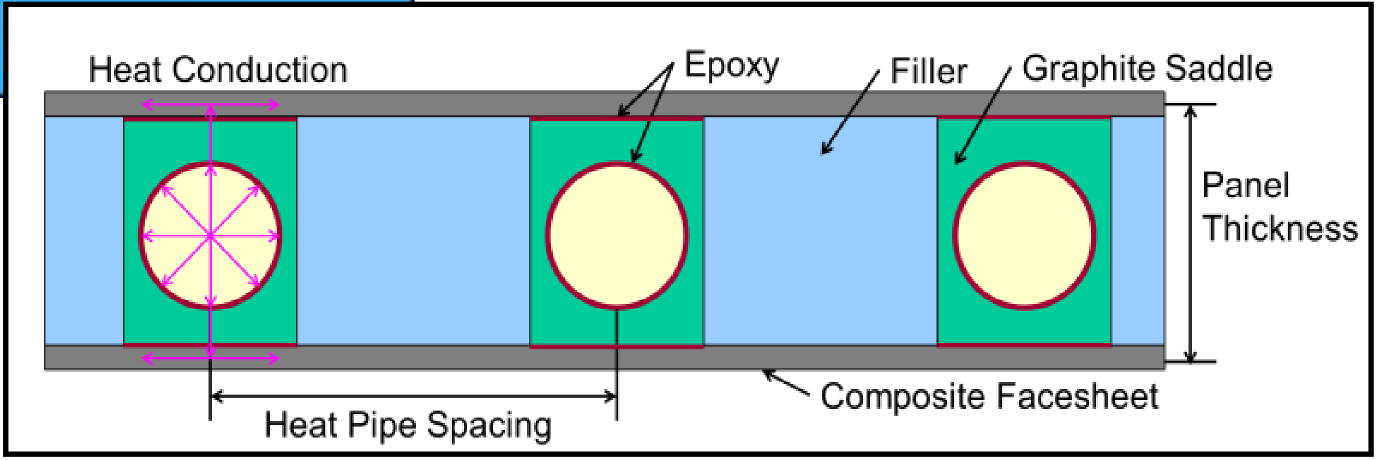
Typical Fin Constructions

Wrapped Fin





Structural Panel



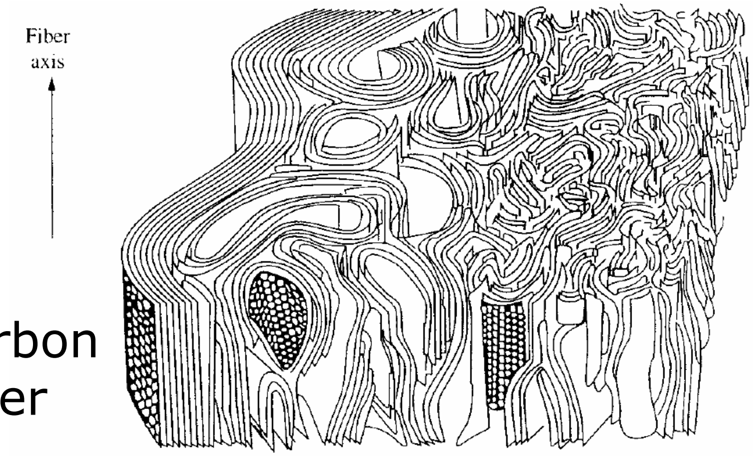
Fin Material Comparison

Fin Material	High Temperature Tolerance (Want HIGH)	Axial Thermal Conductivity (Want HIGH)	Density (Want LOW)
Aluminum	Low	Moderate	Low
Stainless Steel	Moderate	Low	Moderate
Molybdenum	High	Moderate	High
Carbon-Carbon Composite	High	Moderate	Low
Carbon-Polymer Composite	Low	Moderate	Moderate
Bare Carbon Fiber	High	High	Low

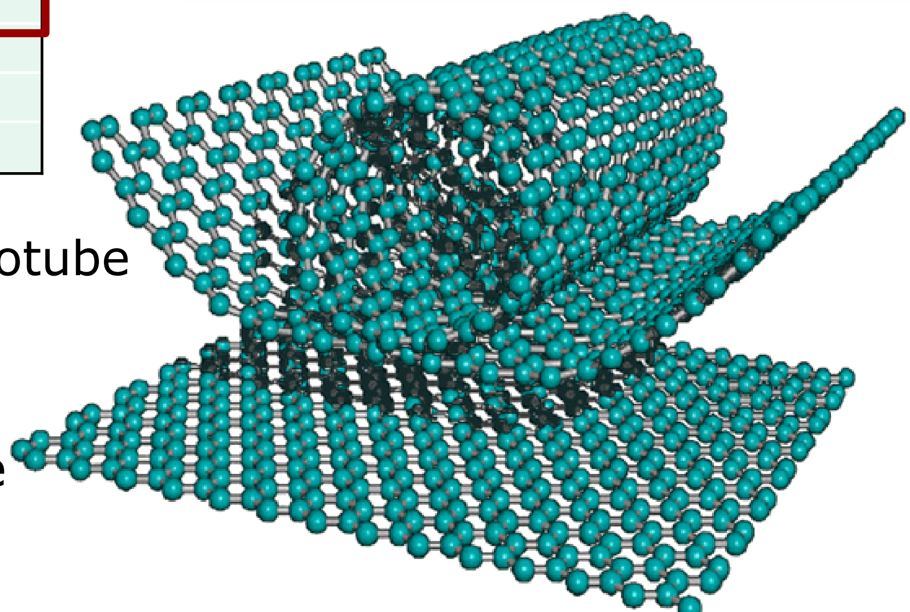
Materials

Thermal Conductivity of Carbon Materials

Measured Axial/In-Plane Thermal Conductivity at Room Temperature (300K) [W/(m-K)]	
Graphene Sheet	3080–5300
Carbon Nanotube (CNT)	
Single-Walled (SW)	3500
Multi-Walled (MW)	3000
SW-CNT Bundles	1750-5800
Diamond	2200
Carbon Fiber	600-1500
Natural Graphite	130
CNT Cloth	40, 250 (600°C)
CNT "As-Grown" Mat	35



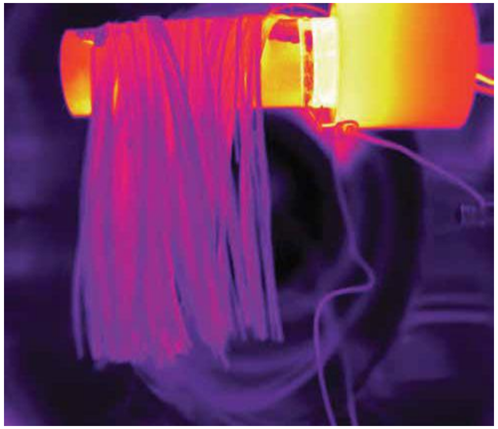
Carbon Fiber



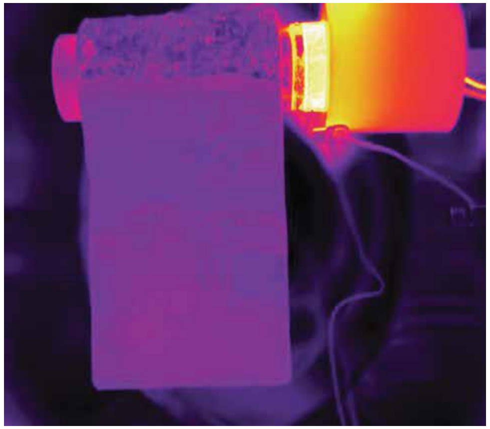
Carbon Nanotube → Graphene

Image: [67]

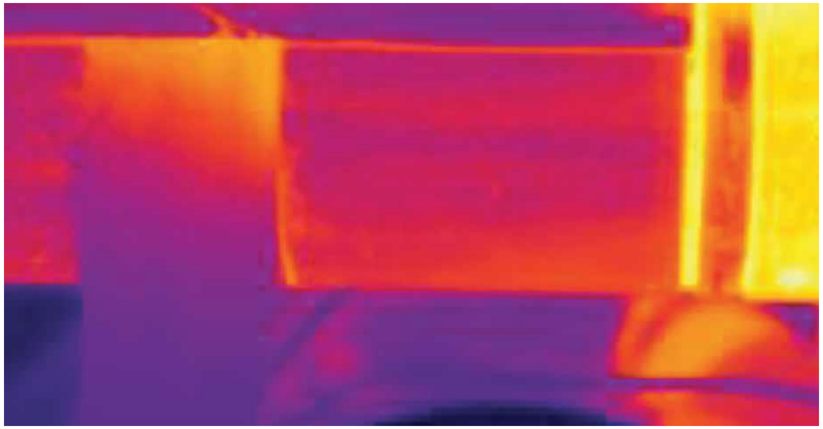
Materials Used in Test



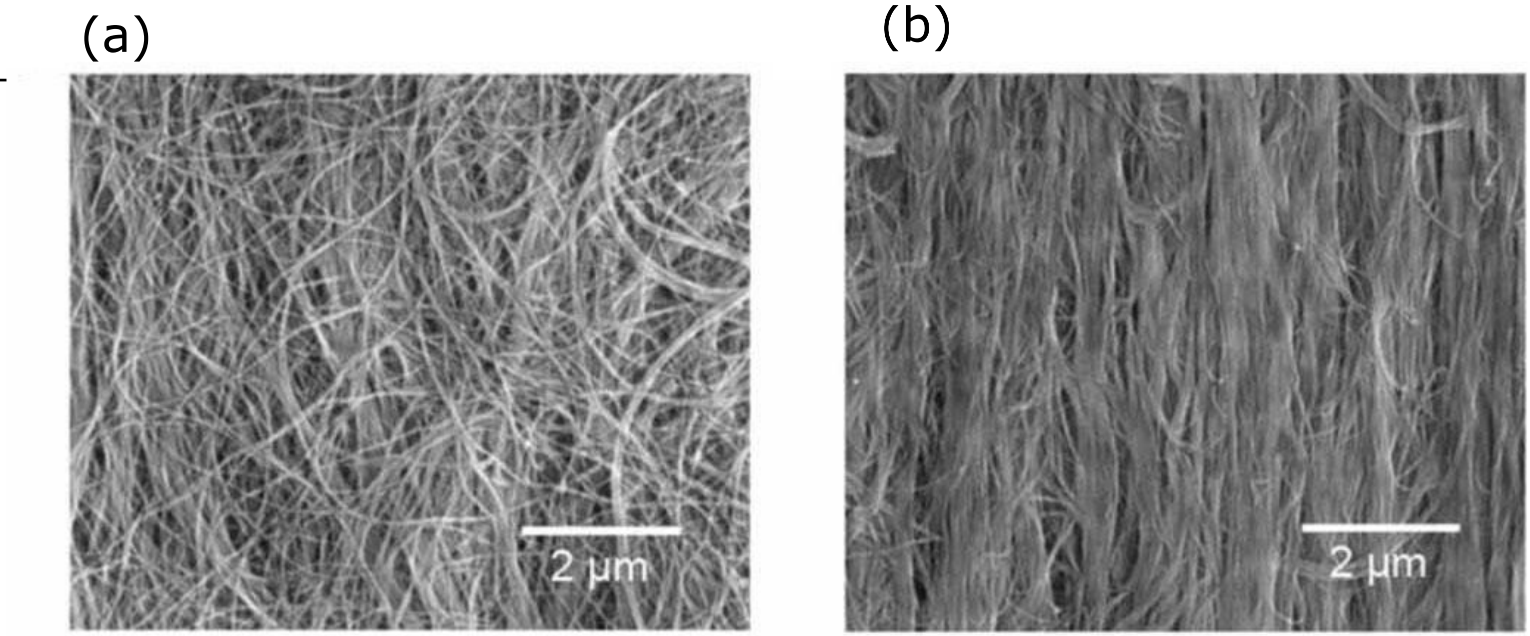
IR image of carbon fibers with a heater temperature of 600°C.



IR image of carbon nanotube cloth with a heater temperature of 600°C.



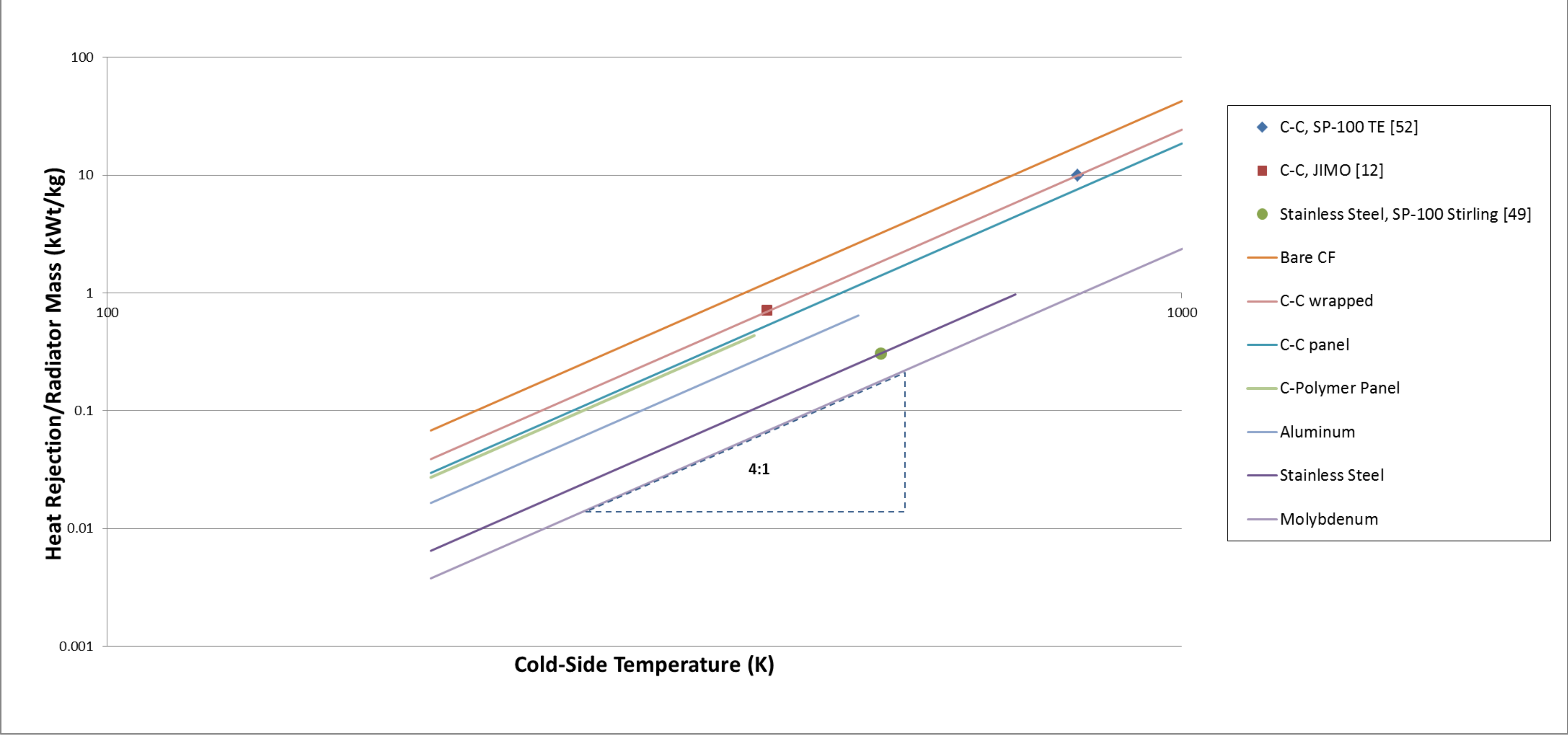
IR image of oriented CNT composite (Dennis Tucker) with a heater temperature of 600°C.



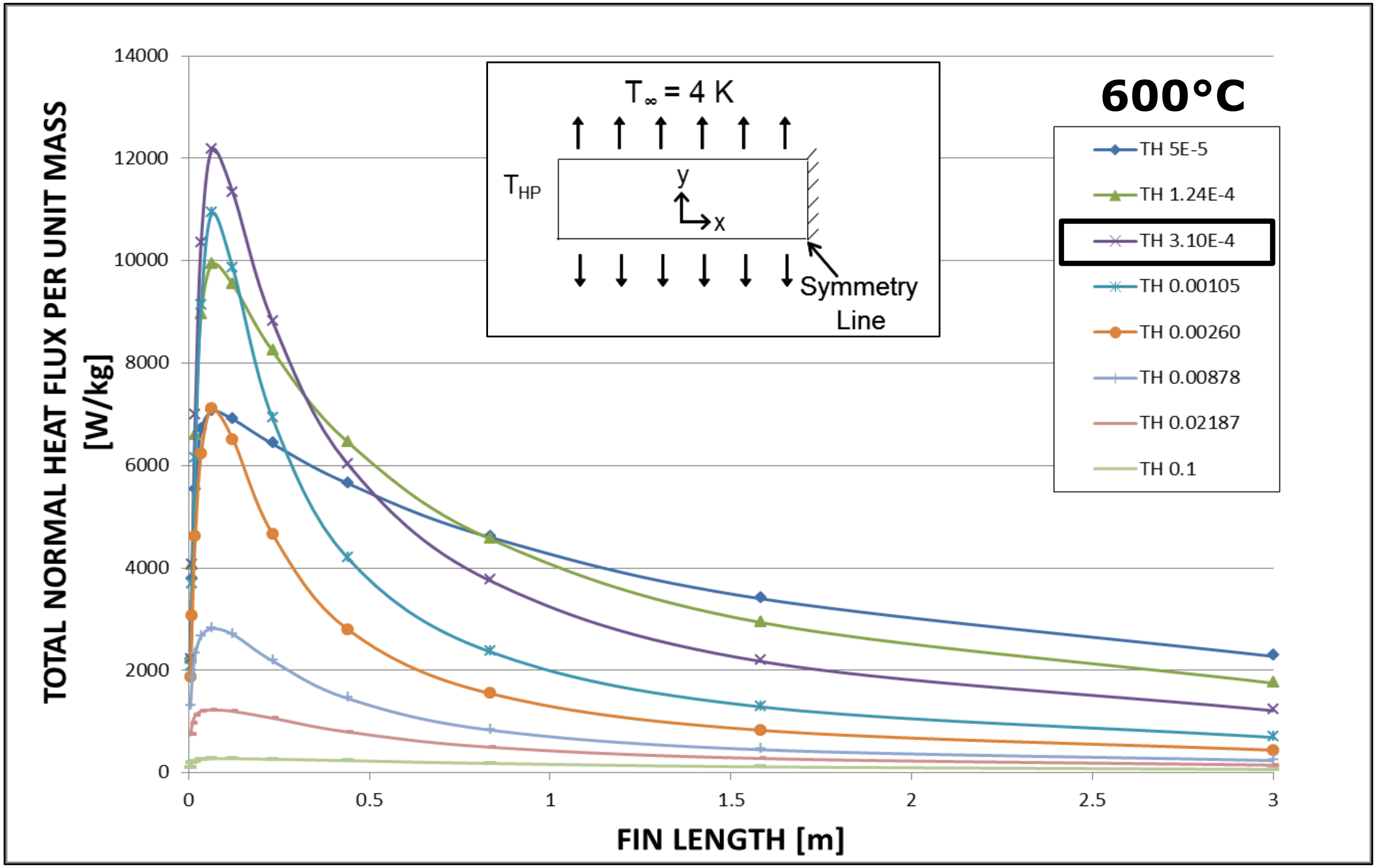
(a) An unstretched composite sheet with wavy nanotubes and microscale porous structure and (b) a composite sheet stretched by 12%, showing straight, well-aligned and closely-packed nanotubes.[*]

*X. Wang, Z. Z. Yong, Q. W. Li, P. D. Bradford, W. Liu, D. S. Tucker, W. Cai, H. Wang, F. G. Yuan & Y. T. Zhu (2012): Ultrastrong, Stiff and Multifunctional Carbon Nanotube Composites, Materials Research Letters, DOI:10.1080/21663831.2012.686586

Fin Material Comparison



Fin Geometry Optimization

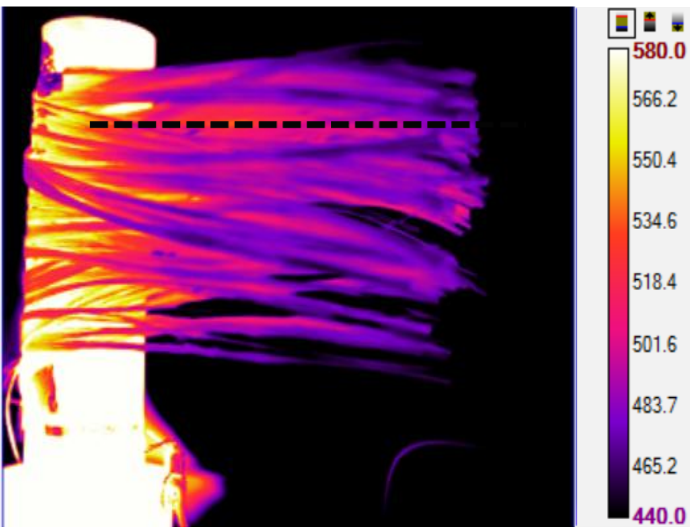


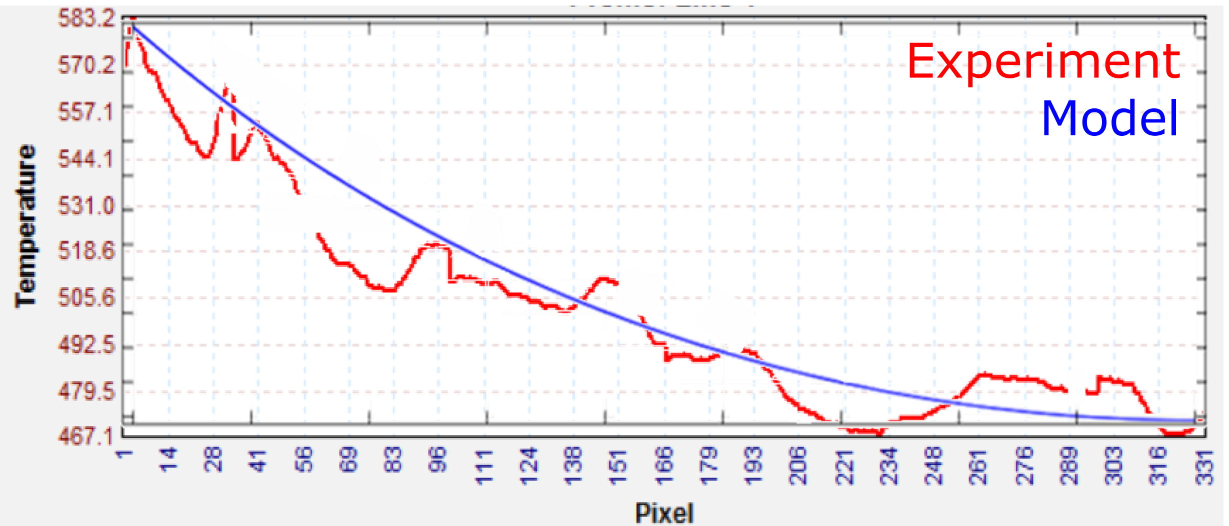
Preliminary Tests

- Test artice: Inconel 718 pipe, TiCuSil braze, Mitsubishi KI3C2U (pitch) carbon fiber
- Evaluate basic fin performance and component compatibility
- Verify imaging capabilities
- Validate basic model

Model Progress

- May campaign: good qualitative fit





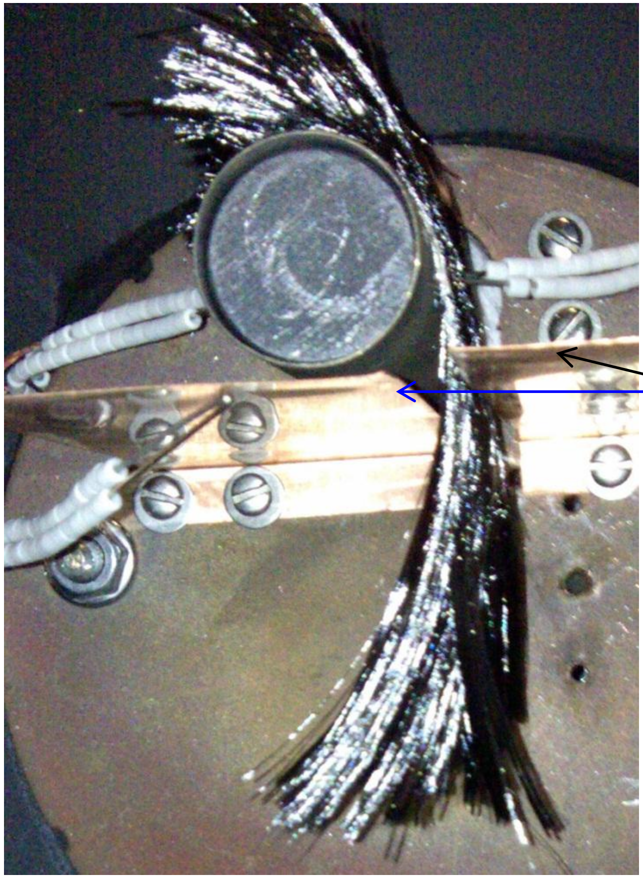
$$t_{meas} = \frac{\left({}^{mass}\!/_{length} \right)}{(density)(width)}$$

Unshielded Fin

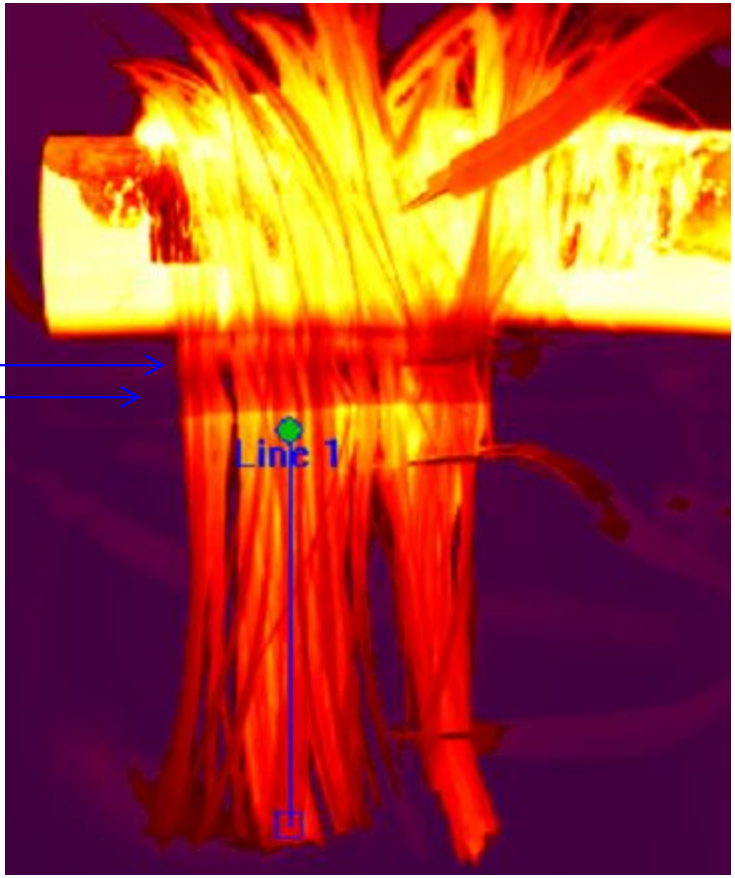
- Each element of the fin is heated by direct radiation from the tube, as well as by conduction along fin.
- Analytic calculation shows radiation from tube is about 9.8W/m of width, vs. conduction about 7.4 W/m.
- Total heat transfer is sum of radiation and conduction.
- Apparent thickness would be 2.3 X measured.
- Discrepancy between model and experiment explained.

Shielded Fin

- Isolate conduction along fin
- Water-cooled copper heat shields added.



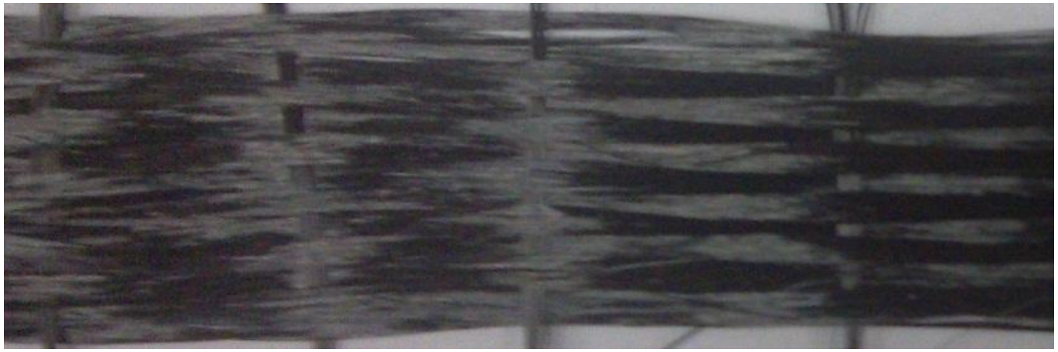
Shields



Lessons from Comparison of Model and Experiment

- Quantitative agreement between model and experiment for best samples, shielded fins.
- Large variability in temperature distribution in IR images, particularly for irregular samples.
  - Need very controlled sample geometry
  - Braided fiber specimens?

Woven High-conductivity Carbon Fiber

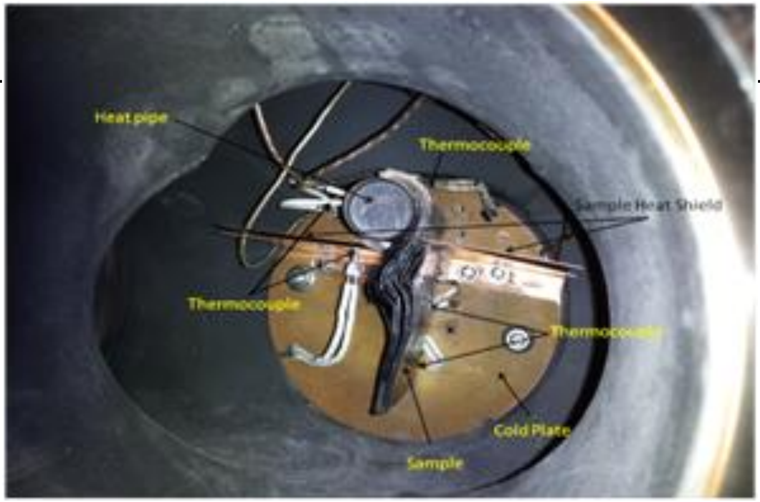


Woven carbon fiber manufacturing pathfinder, made at MSFC from Mitsubishi K13D2U high-conductivity carbon fiber. This article is approximately 30 cm x 3 and contains 30 tows, approximately 90,000 carbon fibers.

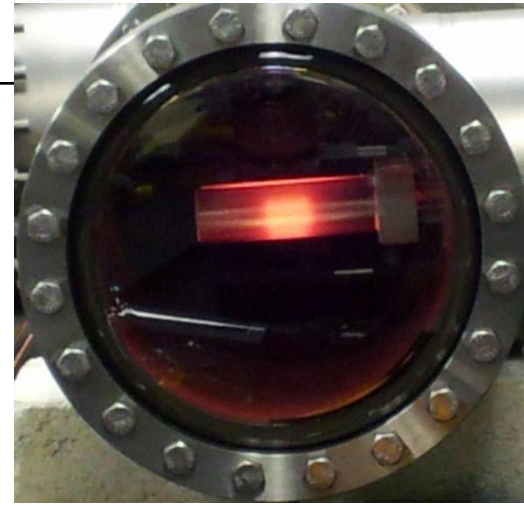
Commercial unidirectional carbon structural fiber

First generation article brazed from individual tows.

Facilities / Components

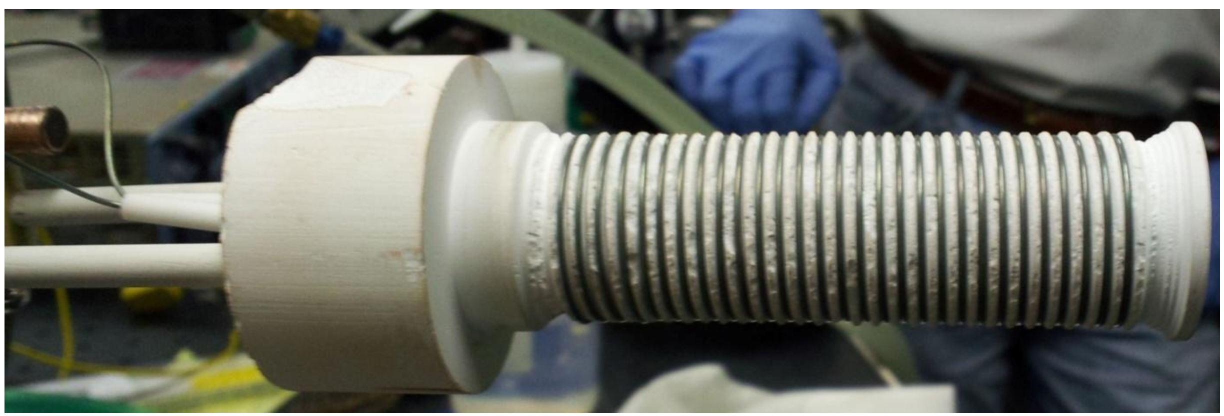


Generic Heater Setup



Vacuum Braze Facility

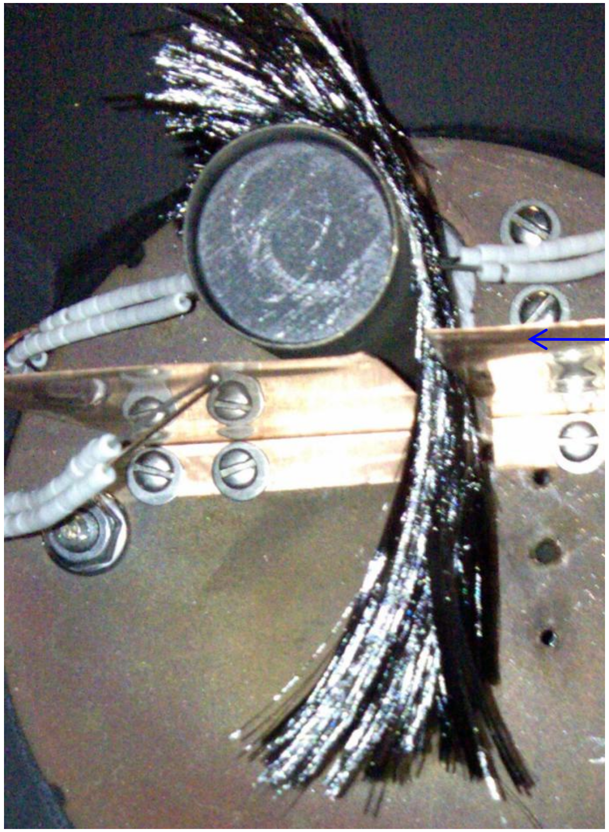
Sample Braze



Latest Version of Heat source for Radiator and Braze Facility

Shielding Fins

- Isolate conduction along fin
- Water-cooled copper heat shields added.

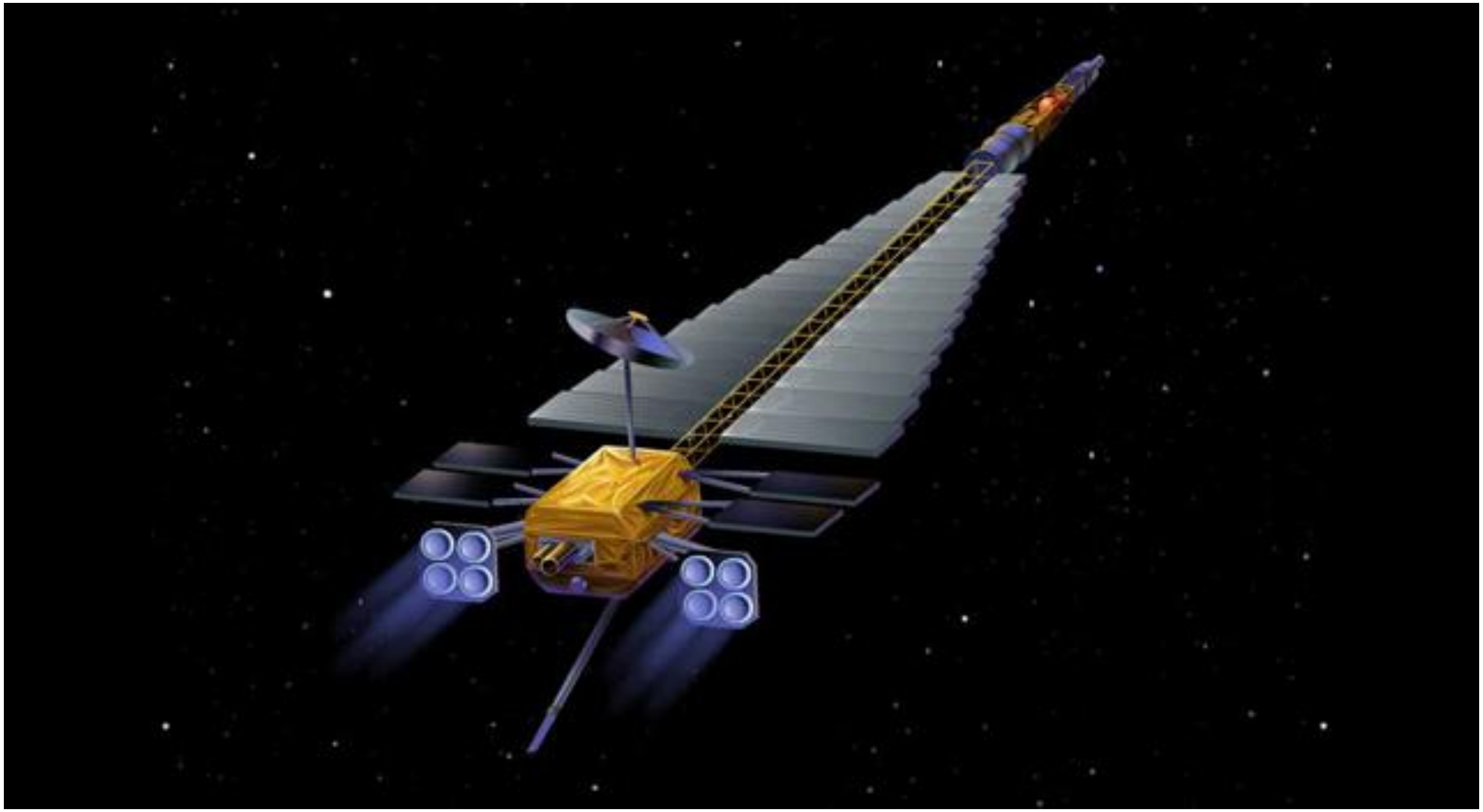


Shields

Future Work

- Increase the upper operating temperature
- Quantify device performance
- Assess the potential of such devices and materials to meet NASA's needs for high-temperature radiators for spacecraft
- Recommend further refinement and characterization of similar devices

Questions



References

- [1] S.M. Canepari, L.A. Bellini, K.J. Riley, and R.W. Hyers, “Damage-Tolerant, Lightweight, High-Temperature Radiator for Nuclear Powered Spacecraft”, Final Report, University of Massachusetts Healey Endowment Grant, July 2006.
- [2] http://www.nasa.gov/pdf/503466main_space_tech_grand_challenges_12_02_10.pdf (accessed 11/5/2011)
- [3] S.L.Rodgers, “Propulsion Research Center.” Proceedings of the Workshop on Materials Science for Advanced Space Propulsion, Huntsville, Alabama, October 9-10, 2001.
- [4] E.M. Sparrow, R.D. Cess. “Radiation Heat Transfer.” Hemisphere Publishing Corporation, Washington 1978.
- [5] “Voyager: The Interstellar Mission.” http://voyager.jpl.nasa.gov/mission/interstellar.html (accessed 5/15/12).
- [6] Metzger, Brian and Hyers, Robert. “Advanced Carbon-Fiber Radiator for Space-Based Power Conversion”. Healey Proposal, 2005.
- [7] V.J. Lyons, *et. al*., “Draft Space Power and Energy Storage Roadmap, Technology Area 03,” NASA Office of the Chief Technologist, November, 2010.
- [8] M.Meyer, *et. al*., “Draft In-Space Propulsion Systems Roadmap, Technology Area 02,” NASA Office of the Chief Technologist, November, 2010.
- [9] S.A. Hill, *et. al*., “Draft Thermal Management Systems Roadmap, Technology Area 14,” NASA Office of the Chief Technologist, November, 2010.
- [10] http://www.aerospaceguide.net/spacecraft/jimo.html (accessed 11/20/2011)
- [11] L.S. Mason, *et. al*., “Fission Surface Power System Initial Concept Definition,” NASA Technical Memorandum 216772, August 2010.
- [12] L.S. Mason. “A Power Conversion Concept for the Jupiter Icy Moons Orbiter.” Journal of Propulsion and Power, Vol. 20, No. 5, September–October 2004.
- [13] L.S. Mason, *et. al*. “Design and Test Plans for a Non-Nuclear Fission Power System Technology Demonstration Unit.” Proceedings of Nuclear and Emerging Technologies for Space, Albuquerque, NM, February 7-10, 2011, Paper 3327.
- [14] D. Ellis, *et. al*. “Summary of the Manufacture, Testing and Model Validation of a Full-Scale Radiator for Fission Surface Power Applications.” Proceedings of Nuclear and Emerging Technologies for Space, Albuquerque, NM, February 7-10, 2011, Paper 3181.
- [15] N.M. Teti. “Carbon-Carbon Radiator Validation Report.” Swales Aerospace, February 2002.
- [16] L.S. Mason. “Recent Advances in Power Conversion and Heat Rejection Technology for Fission Surface Power.” NASA Technical Memorandum 216761, July 2010.
- [17] A.J. Juhasz and G.P. Peterson, “Review of Advanced Radiator Technologies for Spacecraft Power Systems and Space Thermal Control”, NASA Technical Memorandum 4555, 1994.
- [18]”Jupiter Icy Moons Orbiter.” http://en.wikipedia.org/wiki/Jupiter_Icy_Moons_Orbiter (accessed 12/9/2011).
- [19] “Atlas V Launch Services User’s Guide.” United Launch Alliance, and Lockheed Martin. March 2010.
- [20] “Mars Exploration Program.” http://marsprogram.jpl.nasa.gov/programmissions/ (accessed 1/13/2012)
- [21] “Innovative Interstellar Explorer.” http://interstellarexplorer.jhuapl.edu/spacecraft/eng_req.html (accessed 1/13 2012).
- [22] G.L. Bennett. “Space Nuclear Power: Opening the Final Frontier.” AIAA 4th International Energy Conversion Engineering Conference, San Diego, CA June 2006.
- [23] NASA Factsheet “Juno Mission to Mars” Jet Propulsion Laboratory, Pasadena, CA. http://www.nasa.gov/pdf/316306main_JunoFactSheet_2009sm.pdf (accessed 1/13/2012)
- [24] “SNAP Overview.” U.S. Department of Energy. http://etec.energy.gov/Operations/Major_Operations/SNAP_Overview.html (accessed January 13, 2012)
- [25] “Nuclear Powered Space Missions: Past and Future.” http://www.space4peace.org/ianus/npsm2.htm (accessed 1/13/2012)
- [26] “External Tank-119 Leaves Michoud Assembly Facility” http://www.nasa.gov/centers/marshall/michoud/shuttle_et119_1.html (accessed January 14, 2012)
- [27] “Liquid Metal Operations”. Energy Technology Engineering Project Closure Report. http://www.etec.energy.gov/History/Sodium/Sodium-index.html (accessed January 16, 2012).
- [28] NASA Glossary: Astronomical Unit. http://neo.jpl.nasa.gov/glossary/au.html (accesses January 16, 2012).
- [29] D.M. Goebel, I. Katz. “Fundamentals of Electric Propulsion: Ion and Hall Thrusters.” Jet Propulsion Laboratory California Institute of Technology, March 2008.
- [30] R.R Hofer, K.H. Grys, *et. al.* “Evaluation of a 4.5 kW Commercial Hall Thruster System for NASA Science Missions.” 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2006, Sacramento, CA.
- [31] M.D. Rayman, *et. al.* “Results from the Deep Space 1 Technology Validation Mission.” Acta Astronautica 47, pg. 475, (2000).

References Continued

- [32] M.D. Rayman. "The Successful Conclusion of the Deep Space 1 Mission: Important Results without a Flashy Title." Space Technology 23, Nos. 2-3, pg. 185 (2003).
- [33] Boeing: NSTAR Ion Thruster Factsheet. http://www.boeing.com/defense-space/space/bss/factsheets/xips/nstar/ionengine.html (accessed January 18, 2012).
- [34] J. Siamidis, L. Mason, *et. al.* "Heat Rejection Concepts for Brayton Power Conversion Systems." NASA Technical Memorandum #213337 (2005).
- [35] R.F. Mather. "Nuclear Reactor Space Power Conversion Systems."
- [36] D. Archer, et. al. "The NEPTUNE Power System: a Boiling Potassium Space Nuclear Power/Propulsion Reactor System Final Report." Texas A&M University (1989).
- [37] http://www.daviddarling.info/encyclopedia/H/Halleffectthruster.html (accessed 3/12/12).
- [38] H.B. Denham, J.K. Koester, W. Clarke, A.J. Juhasz. "NASA Advanced Radiator C-C Fin Development." American Institute of Physics Conference Proceedings, 301, p. 1119 (1994).
- [39] D.G. Gilmore. "Satellite Thermal Control Handbook." The Aerospace Corporation Press, CA (1994).
- [40] A.F. Henry. "Nuclear-Reactor Analysis." The Massachusetts Institute of Technology Press, Cambridge, MA (1975).
- [41] J. Weisman. "Elements of Nuclear Reactor Design." ElSevier Scientific Publishing Company, New York (1977).
- [42] B.A. Cook. "Making Space Nuclear Power a Reality." AIAA 1st. Space Exploration Conference : Continuing the Voyage of Discovery, Orlando, Florida, January 30 - February 1, 2005.
- [43] J. Siamidis. "Heat Rejection Concepts for Lunar Fission Surface Power Applications." NASA Technical Memorandum #214388 (2006).
- [44] "Ideal Brayton Cycle." Glenn Research Center. http://www.grc.nasa.gov/WWW/k-12/airplane/brayton.html (accessed March 4, 2012).
- [45] "Gas Power Cycles." https://wiki.ucl.ac.uk/display/MechEngThermodyn/Gas+Power+Cycles (accessed March 4, 2012).
- [46] D. Porter. "NASA Power Systems: Research in New Energy Technology." Purdue Outreach Presentation (2007).
- [47] S. Aftergood. "Background on Space Nuclear Power." Science & Global Security, v.1, pp93-107 (1989).
- [48] "What is BRDF?" http://www.scratchapixel.com/lessons/3d-advanced-lessons/things-to-know-about-the-cg-lighting-pipeline/what-is-a-brdf/ (accessed 6/6/12).
- [49] L. Mason, H.S. Bloomfield. "SP-100 Power System Conceptual Design for Lunar Base Applications." NASA Technical Memorandum #102090 (1989).
- [50] "Prometheus Project Final Report." Jet Propulsion Laboratory, NASA Report #982-R120461 (2005).
- [51] J.F. Mondt, V.C. Truscello, A.T. Marriot. "SP-100 Power Program." Jet Propulsion Laboratory, NASA Report (1994).
- [52] A.J. Juhasz, R.D. Rovang. "Composite Heat Pipe Development Status: Development of Lightweight Prototype Carbon-Carbon Heat Pipe with Integral Fins and Foil Liner." NASA Technical Memo #106909, and Presented at the Ninth International Heat Pipe Conference, Albuquerque, NM (1995).
- [53] "Lambert's Cosine Law." http://en.wikipedia.org/wiki/Lambert's_cosine_law (accessed 6/6/12).
- [54] M.G. Houts. "Space Nuclear Power and Propulsion: Materials Challenges for the 21st Century." Presentation from the National Space and Missile Materials Symposium, June 24, 2008.
- [55] J.P. Fleurial, *et. al.* "Development of Segmented Thermoelectric Multicouple Converter Technology." IEEE Aerospace Conference, Big Sky, Montana, March 04-11, 2006.
- [56] "Thermionic Converter." http://www.propagation.gatech.edu/ECE6390/project/Fall2010/Projects/group8/power.html (accessed 3/28/12).
- [57] "Themoeletric Generator." http://www.mpoweruk.com/thermoelectricity.htm (accessed 3/28/12).
- [58] P. Pesavento. "From Aelita to the International Space Station: The Psychological and Social Effects of Isolation on Earth and in Space." The History of Spaceflight Quarterly, vol. 8, no. 2, (2000).
- [59] D.William, *et. al*. "Acclimation during space flight: effects on human physiology." Canadian Medical Association Journal, published at www.cmaj.ca, June 9, 2009 (accessed 5/15/12).
- [60] M. Roach. "Packing for Mars: The Curious Science of Life in the Void." W.W. Norton & Company, Copyright 2010.
- [61] "Brief History of Thermoeletrics." http://www.its.caltech.edu/~jsnyder/thermoelectrics/history.html (accessed 6/5/12).
- [62] S. Johnson. "Project Prometheus Two-Phase Flow, Fluid Stability and Dynamics Workshop." NASA Technical Memorandum #212598 (2003).
- [63] J. Chan, J.G. Wood, J.G. Schreiber. "Development of Advanced Stirling Radioisotope Generator for Space Exploration." NASA Technical Memorandum #214806 (2007).
- [64] "Nuclear Reactors for Space." World Nuclear Association. http://www.world-nuclear.org/info/inf82.html (accessed 6/5/12).
- [65] Chan, T.S., Wood, J. G. and Schreiber, J. G., "Development of Advanced Stirling Radioisotope Generator for Space Exploration." NASA Glenn Technical Memorandum #214806 (2007).
- [66] http://f1-dictionary.110mb.com/carbon_fiber.html
- [67] http://www.nanosource.com/Innovation.html
- [68] http://www.1-act.com/newsitems/view/65/ACT_Delivers_Titanium_Heat_Pipe_Radiator_Demonstration_Units_to_NASA

BACKUP SLIDES

Radiators are an Essential Cross Discipline Supporting Technology

- ***TA02 In-Space Propulsion Systems***

Supporting technologies…

2.4.4 Heat Rejection

Heat rejection is a key supporting capability for several in space propulsion systems. Some examples include rejection of the waste heat generated due to inefficiencies in electric propulsion devices … In general the key heat rejection system metrics for in-space propulsion are cost, weight, operating temperature, and environmental durability (e.g. radiation, MMOD).[1]

- ***TA03 Space Power and Energy Storage***

5.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy:…. "Fission: Nuclear reactor systems can provide relatively high power over long periods of time. … Other components have reached higher TRLs in past programs such as the SP-100 and Prometheus programs, but technology capability has been lost and must be redeveloped. Key subsystems that must be addressed include … heat transfer, heat rejection…."[3]

- ***TA14 Thermal Management Systems***

2.2.3.1. Radiators

Radiator advancement is perhaps the most critical thermal technology development for future spacecraft and space-based systems. Since radiators contribute a substantial portion of the thermal control system mass. For example, the Altair (Lunar Lander) vehicle radiator design represents 40% of the thermal system mass. Radiators can be subdivided into two categories; the first is for rejection at temperatures below 350 K and the second is for nuclear or high power systems at temperatures around 500 K.[2]

Stated Goals

- A test bed facility and methods for quantification of the performance of radiators made from novel materials
- Demonstration of fabrication methods for novel radiators
- A validated predictive model to support future design and analysis efforts
- Quantification of device performance/assessment of potential.
- Identification of refinements to improve the model and device design.
- Model validation against the experimental results
- Integrate modeling efforts with the test efforts so that test data can be used to anchor and validate the existing model
- Assessment of the potential of such devices to meet NASA’s needs for high-temperature radiators for spacecraft
- Recommendations for further refinement and characterization of similar devices

Accomplishments

- The use of carbon fibers for the radiator material.
- The fabrication and testing of several sub-scale test articles.
- The quantitative agreement between modeled and experimental temperature distribution.
- The design and construction of a heater arrangement that isolates the conductive properties of the samples from the radiative effects of the heat pipe.
- The construction of a vacuum brazing facility for attaching the carbon based fibers to the heat pipe simulator.

Score Card

Stated Objectives

- A test bed facility and methods for quantification of the performance of radiators made from novel materials.
- Identification of refinements to improve the model and device design
- Demonstration of fabrication methods for novel radiators.
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Accomplishments

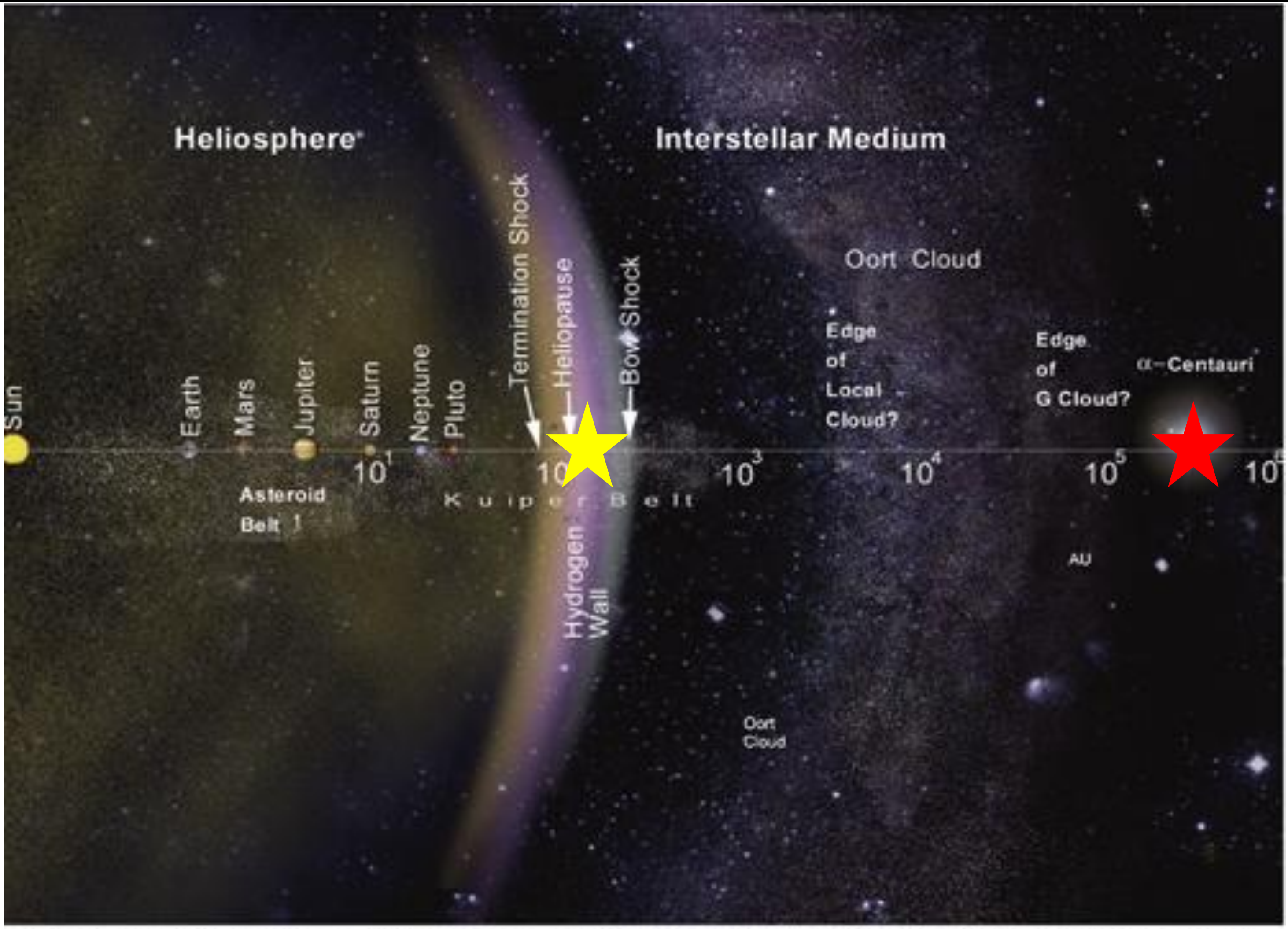
- The design and construction of a heater arrangement that isolates the conductive properties of the samples from the radiative effects of the heat pipe.
- The construction of a vacuum brazing facility for attaching the carbon based fibers to the heat pipe simulator.
- The use of carbon fibers for the radiator material.
- The fabrication of sample radiator fins.
- The fabrication and testing of several sub-scale test articles.
- The quantitative agreement between modeled and experimental temperature distribution.

Importance of Model

The model is the link between the experiments and the flight radiator. If we can model the experiment accurately, then we can make a quantitative prediction of the performance of a flight radiator.

It is through the model that we transform what is measured (temperature distribution along the sample, areal density, mass, etc) and what we know about the material (emissivity, thermal conductivity, etc.) into a useful measure in a full scale model of radiative power/mass, possibly turndown ratios(very much environment dependent), and anything else used to measure radiator efficiency, keeping four metrics in mind, mass of the radiator, operating temperature, environmental durability, and cost.

Motivation: Farther & Faster Space Exploration



Graphic from the Interstellar Probe Science and Technology Definition Team NASA/JPL

Image: [21]

Objectives

NASA's Objective: Increase efficiency and capabilities of deep-space travel

Improved Propulsion:
Increase power-to-mass & speed

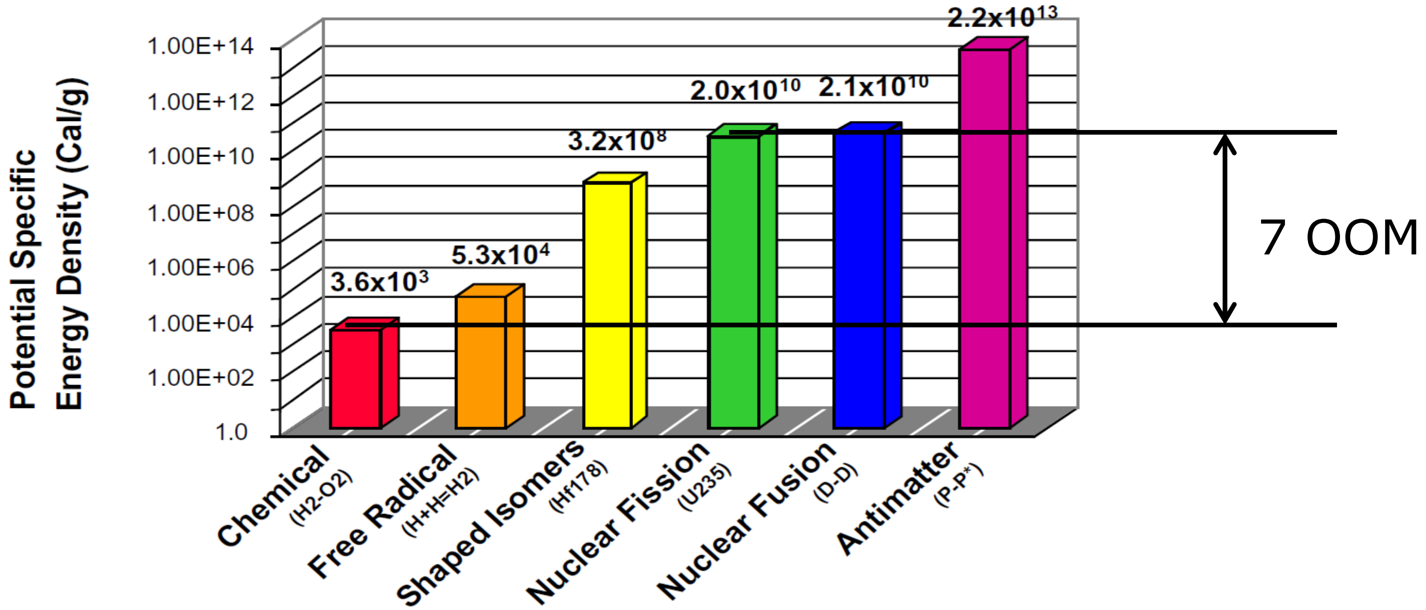
Promising Propulsion Option:
Nuclear-Electric Propulsion (NEP)

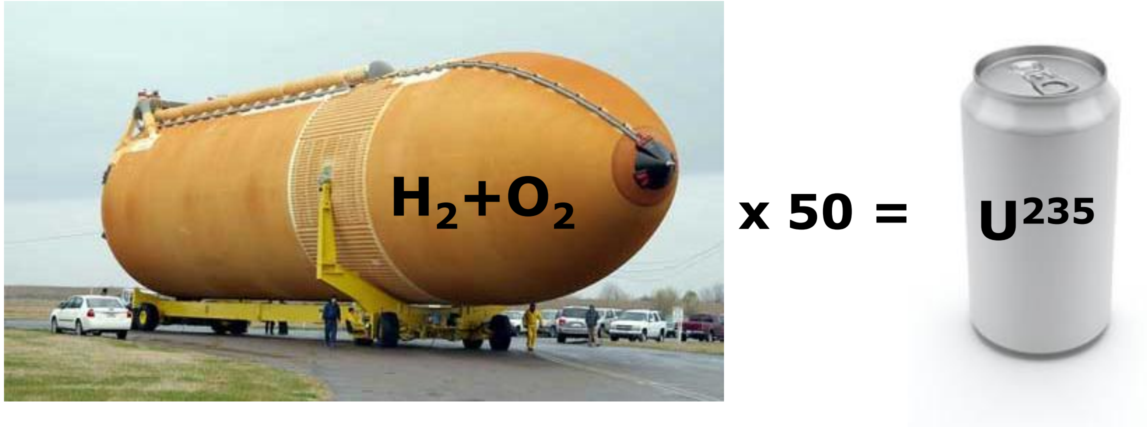
Required Technology for NEP:
Improved Heat Rejection

"*Radiator advancement is perhaps the most critical thermal technology development for future spacecraft and space-based systems*." -NASA

S.A. Hill, *et. al.*, "Draft Thermal Management Systems Roadmap, Technology Area 14," NASA Office of the Chief Technologist, November, 2010.

Potential Propulsion Energy Sources





S.L.Rodgers, "Propulsion Research Center." Proceedings of the Workshop on Materials Science for Advanced Space Propulsion, Huntsville, Alabama, October 9-10, 2001.

Thruster Comparison

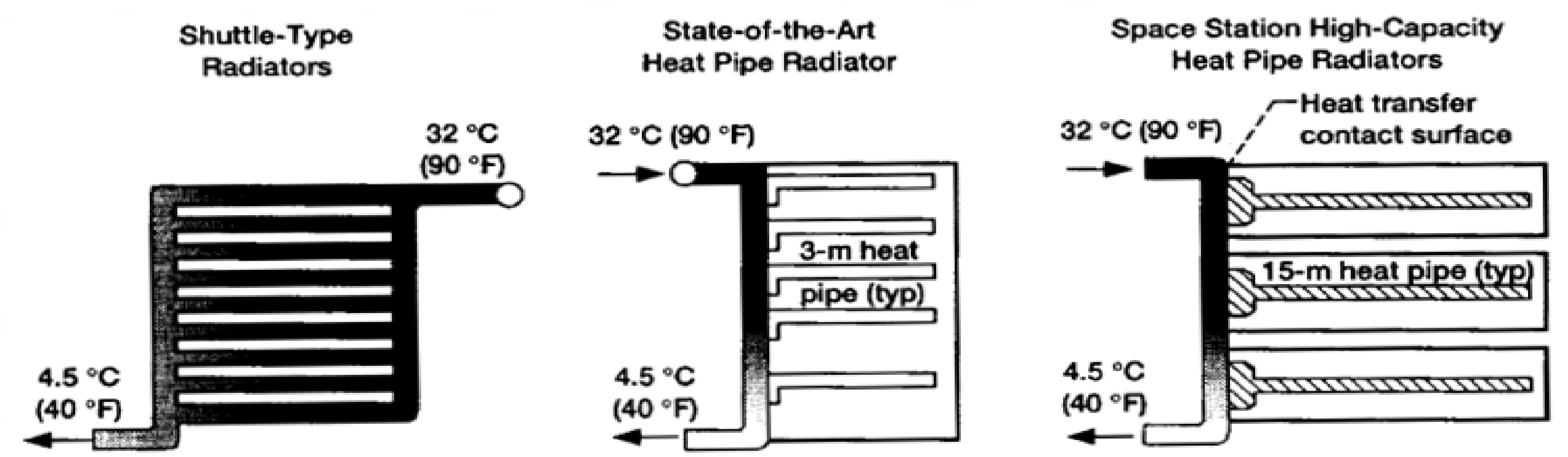
	Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Chemical	Cold gas	50–75	—	—	Various
	Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
	Chemical (bipropellant)	300–450	—	—	Various
Electric	Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
	Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Electrostatic	Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Electrostatic	Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
	PPTs	850–1200	<0.2	7–13	Teflon

$$I_{sp} = \frac{thrust}{(time)(weight\ of\ propellant\ used)} = [1/time]$$

D.M. Goebel, I. Katz. "Fundamentals of Electric Propulsion: Ion and Hall Thrusters." Jet Propulsion Laboratory California Institute of Technology, March 2008.

Heat Transport System Evolution

- Pumped (1970's-1980's)
  - Vulnerable: one pipe failure causes system failure
  - High pumping power required
- Heat Pipe (1990's-present)
  - Independent heat pipes decrease vulnerability
  - 2-phase system quickly transports heat far from source

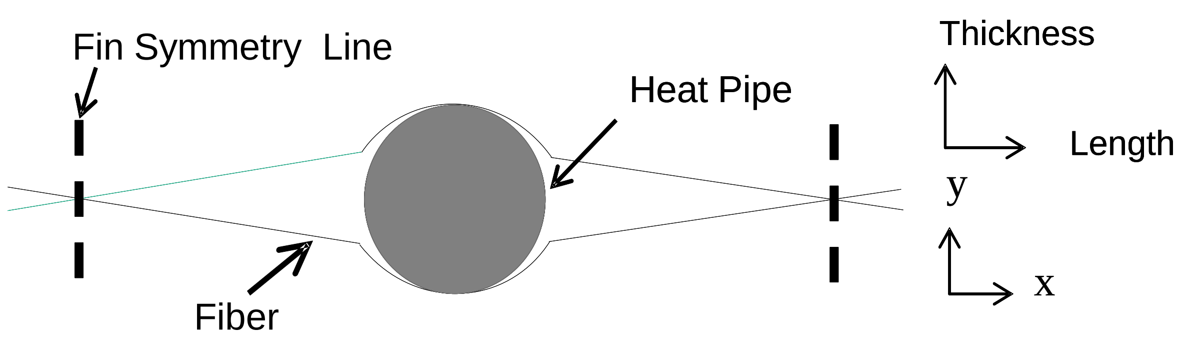


Current Work

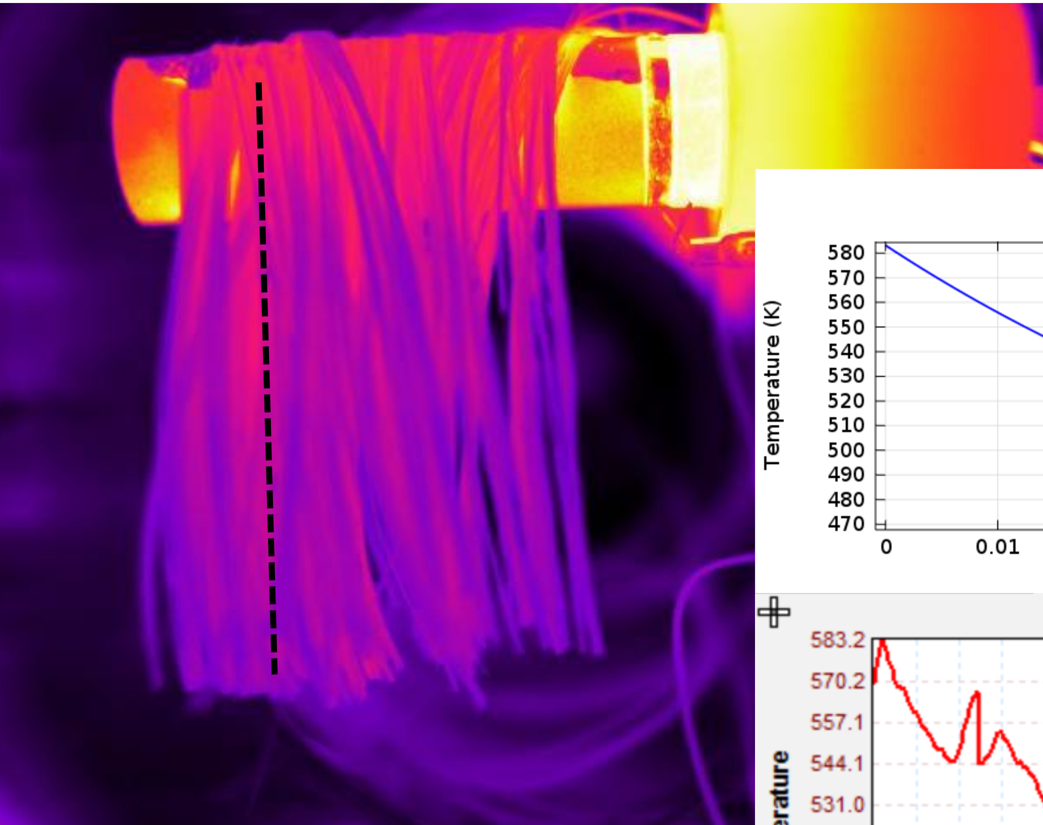
Evaluating bare carbon fiber fin material as a high performing alternative to metals and composites

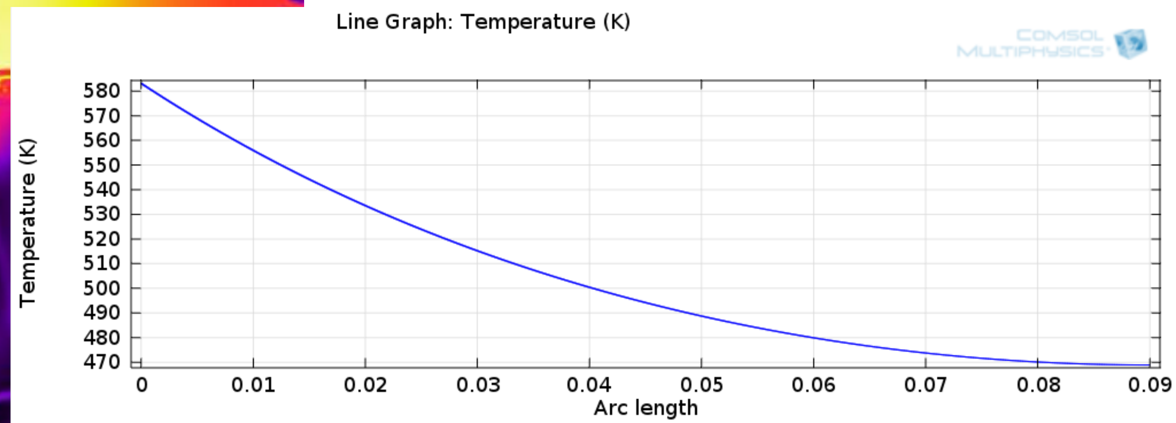
Proposed Carbon Fiber Radiator Fin

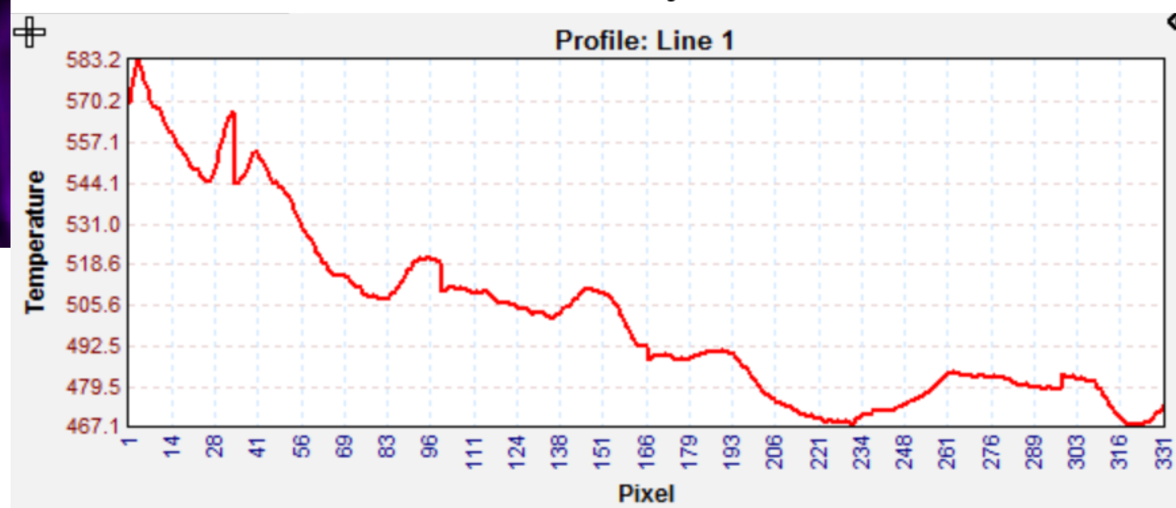
- Replace metal and composite fins with carbon fibers bonded directly to heat pipe
- Eliminate matrix & align majority of fibers normal to heat pipe axis for maximizing thermal performance
- Radiation from top and bottom surfaces



Preliminary Tests

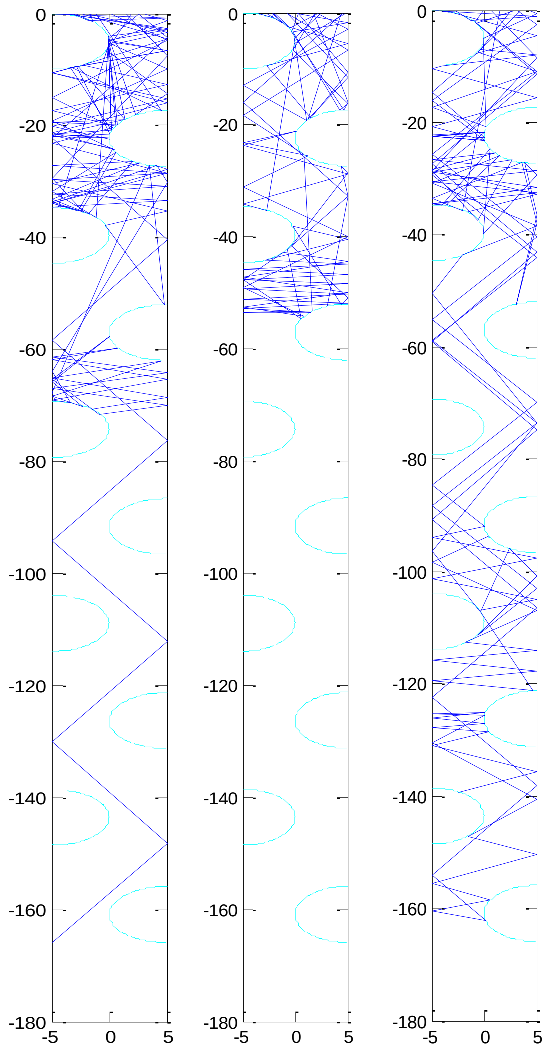




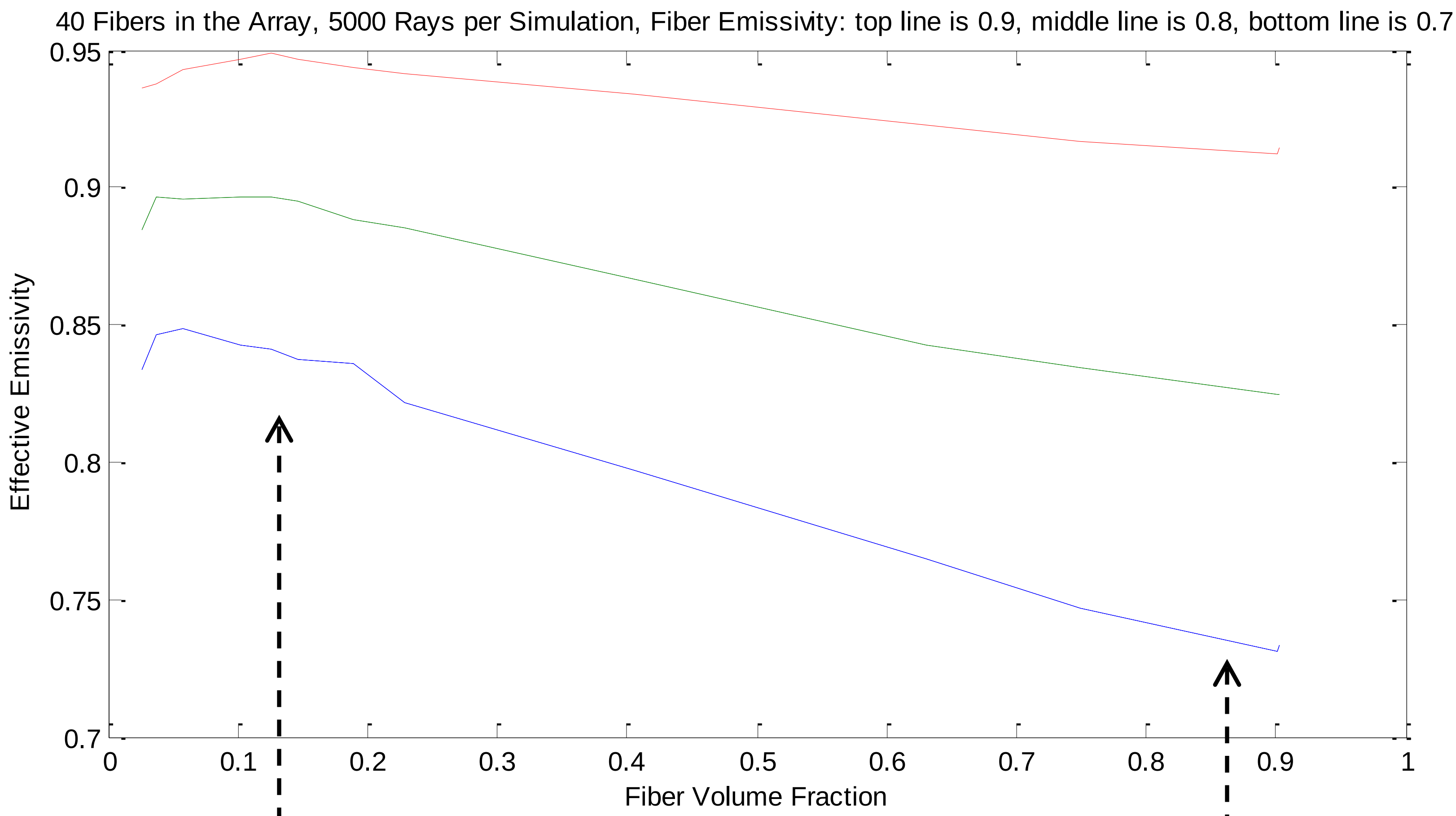


Predicting Fiber Mat Emissivity

- Monte Carlo Ray Tracing
  - Uniform close-packed fibers
  - Diffuse incident radiation from top
  - Gray-Diffuse fibers
  - Symmetry boundary conditions on side walls
  - Top and bottom boundaries are perfect absorbers to scattered radiation
- $\alpha = \varepsilon$ for a grey body



Effective Emissivity Results



Maximum due to multiple scattering within fiber array

Effective emissivity approaches individual fiber emissivity

Fin & Tube Space Radiator Designs Examples

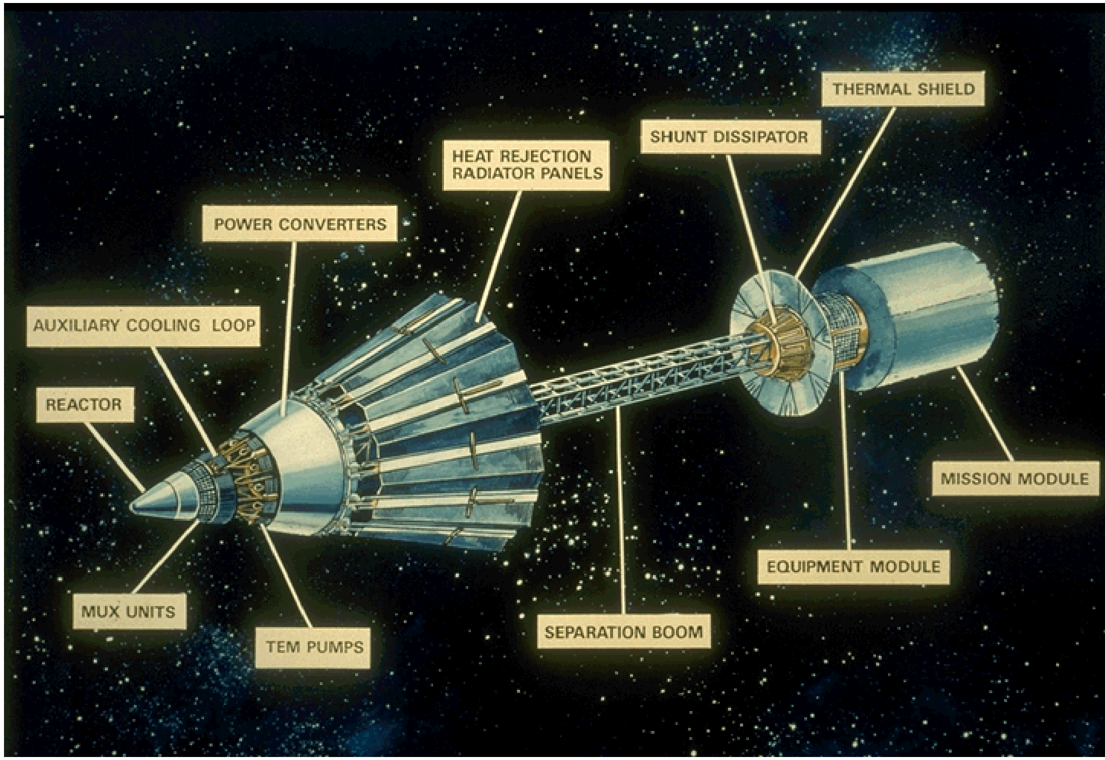
- International Space Station (ISS)
  - Deployable radiator influenced many subsequent designs
  - Implemented, in-use
- Space Power 100kW (SP-100)
  - High-temp, fission power application
  - Designed, not implemented – program ended in 1994
- Jupiter Icy Moon Orbiter (JIMO)
  - NEP application
  - Designed, not implemented – program ended in 2005
- Fission Surface Power (FSP)
  - Fission power application
  - On-going research

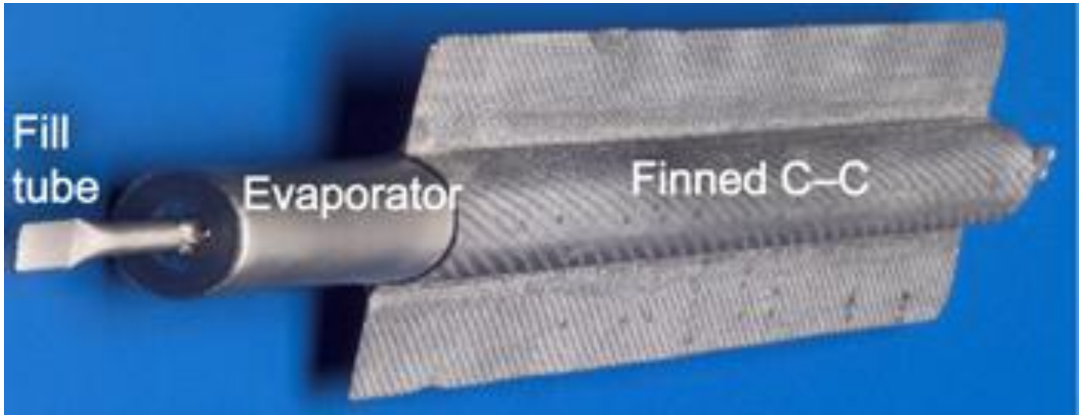
ISS Radiators

- Operating temperature 100°C
- Panels:
  - Aluminum facesheets
  - Aluminum honeycomb filler
  - Inconel tubes
  - Emissive ceramic coating
- Pumped ammonia heat transport system
- Scissor deployment mechanism

SP-100 Radiators

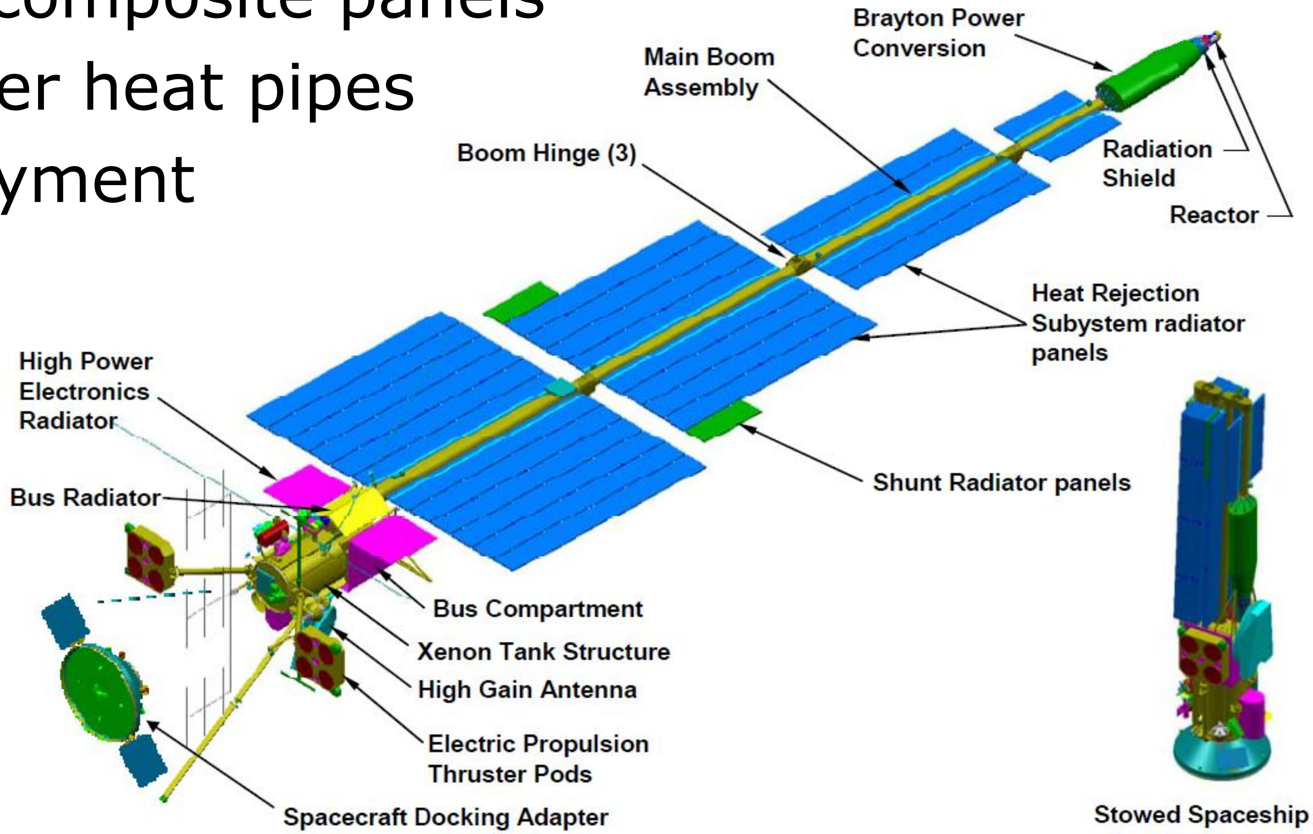
- Operating temp. 600°C
- Main fluid loop: NaK
- C-C composite panels
- Heat Pipe:
  - Niobium-Zirconium shell & wick
  - Potassium fluid





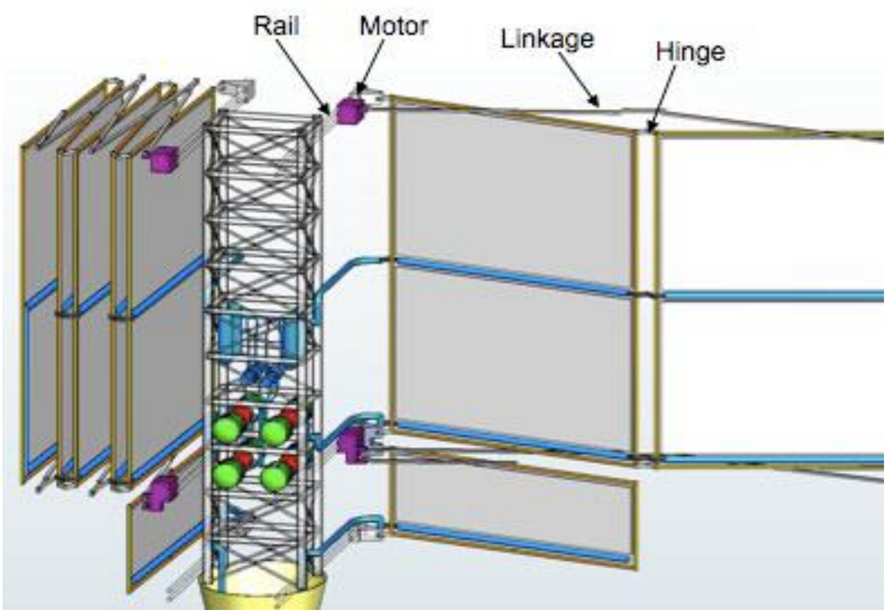
JIMO Radiators

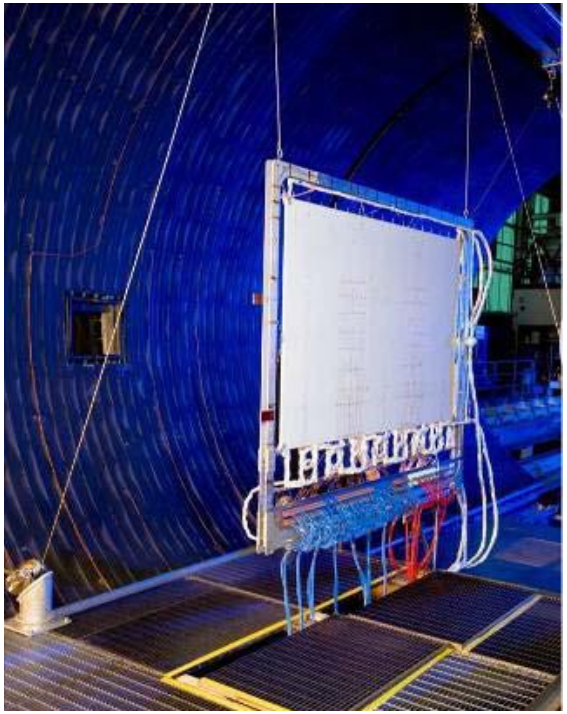
- Operating temperature: 100°C
- Main fluid loop: NaK
- Carbon fiber composite panels
- Titanium-water heat pipes
- Scissor deployment



FSP Radiators

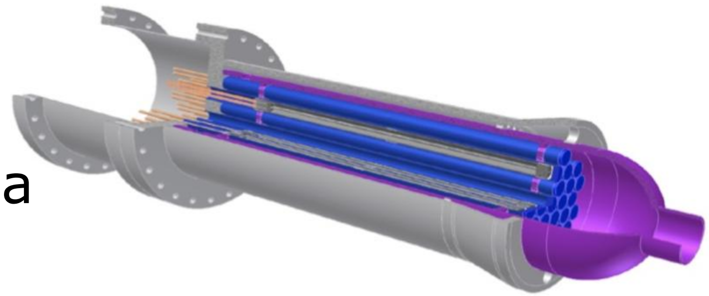
- On-going work on nuclear fission energy for Lunar & Martian outposts
- Continuation of JIMO radiators: 100 °C operating temp., carbon-polymer panels, Ti-water heat pipes, emissive coating
- Demonstration panels →

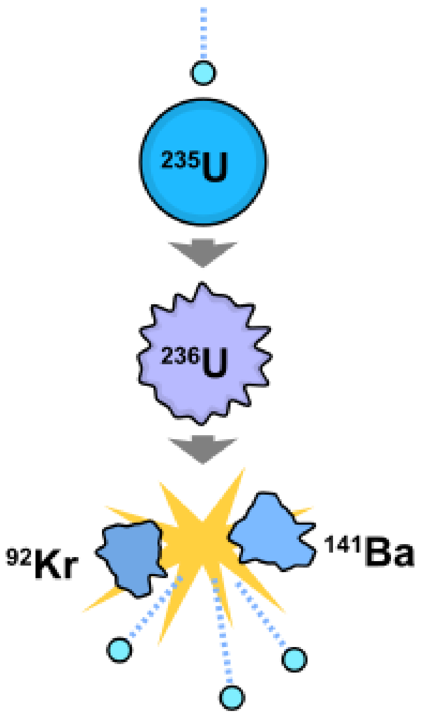




Nuclear Fission Reactor

- Core: fuel elements & working fluid
- Nuclear fission chain reaction:
  1. The nucleus of an atom is struck by a neutron and becomes unstable
  2. Nucleus splits apart in an exothermic reaction releasing kinetic energy of fission products, gamma radiation, and free neutrons
  3. The heat is absorbed by surrounding media and the free neutrons initiate subsequent reactions
- Heat of reaction absorbed by working fluid and delivered to the hot-side of the power generator





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Space Nuclear Reactors

	SNAP-10 US	SP-100 US *	Romashka Russia	Bouk Russia	Topaz-1 Russia	Topaz-2 Russia-US	SAFE-400 US *
dates	1965	1992	1967	1977	1987	1992	2007?
kWt	45.5	2000	40	<100	150	135	400
kWe	0.65	100	0.8	<5	5-10	6	100
converter	t'electric	t'electric	t'electric	t'electric	t'ionic	t'ionic	t'electric
fuel	U-ZrH_x	UN	UC_2	U-Mo	UO_2	UO_2	UN
reactor mass, kg	435	5422	455	<390	320	1061	512
neutron spectrum	thermal	fast	fast	fast	thermal	thermal/ epithermal	fast
control	Be	Be	Be	Be	Be	Be	Be
coolant	NaK	Li	none	NaK	NaK	NaK	Na
core temp. °C, max	585	1377	1900	?	1600	1900?	1020

SNAP-10A

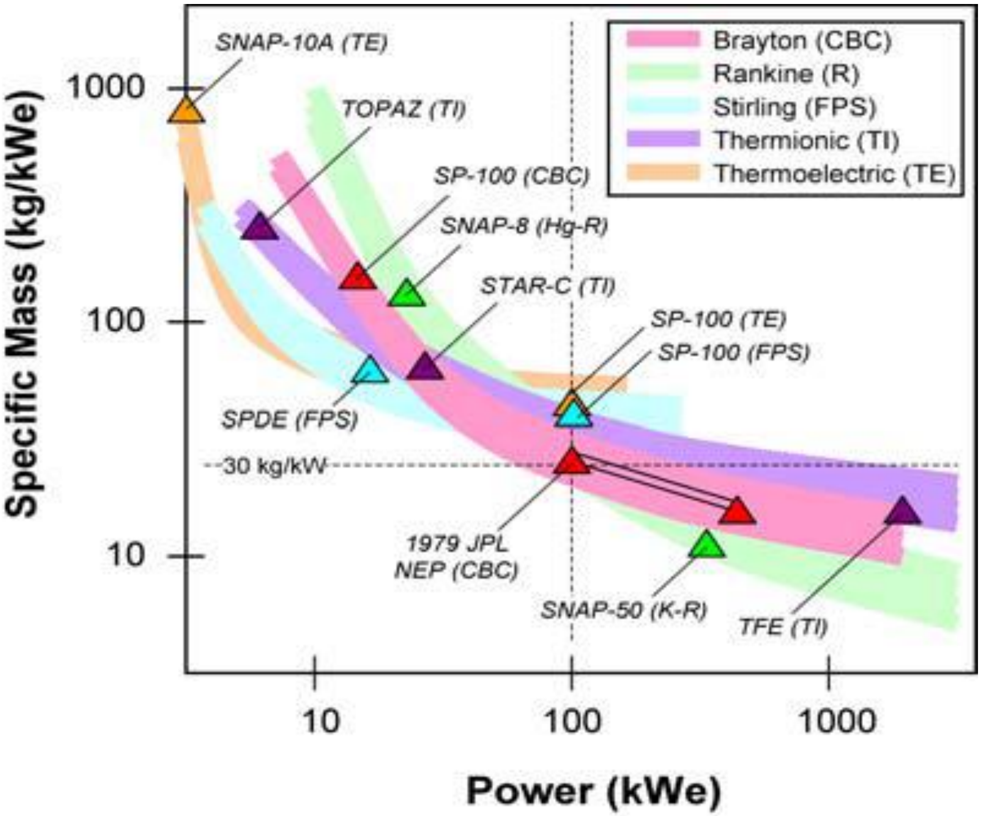
*Designed but not implemented

Total No. Vehicles: ~37 Russian & 1 US

Images: [64,24]

Power Generation Options

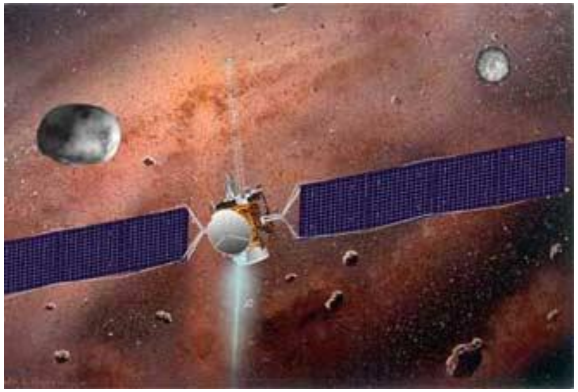
- Dynamic
  - Thermodynamic cycle
  - **Brayton, Stirling**: single-phase
  - Rankine: 2-phase
  - Moderate efficiency (15-30%)
  - Typ. lower-temp.
- Static
  - No moving parts
  - Thermoelectric, Thermionic
  - Typ. low power
  - Low efficiency (1-10%)
  - High-temperature



S. Johnson. "Project Prometheus Two-Phase Flow, Fluid Stability and Dynamics Workshop." NASA Technical Memorandum #212598 (2003).

Spacecraft with Electrostatic Propulsion

- Numerous Earth-orbiting satellites (mostly Russian)
- Deep Space 1 (1998, NASA, ion) first interplanetary probe to test EP with solar power
- Hayabusa (2003, JAXA, ion) study near-Earth asteroid
- SMART-1 (2003, ESA, Hall) orbit Moon, ended with controlled collision
- DAWN (2007, NASA, ion) investigate evolution of small planetary bodies



Advanced Radiator Concepts